

# ERC Direct Carbonate Fuel Cell Program Overview

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## 1.0 INTRODUCTION

The carbonate fuel cell promises highly efficient, cost-effective, environmentally superior power generation from pipeline natural gas, coal gas, biogas, and other gaseous and liquid fuels. ERC has been engaged in the development of this unique technology, focusing on the development of the Direct Fuel Cell (DFC) technology[1,6]. The DFC design incorporates the unique internal reforming feature which allows utilization of a hydrocarbon fuel directly in the fuel cell without requiring any external reforming reactor and associated heat exchange equipment. This approach provides upgrading of waste heat to chemical energy; thereby, it contributes to higher overall efficiency for conversion of fuel energy to electricity with low levels of environmental emissions. Among the internal reforming options, ERC has selected the Indirect Internal Reforming (IIR) - Direct Internal Reforming (DIR) combination as its baseline design. In the IIR-DIR stack, a reforming unit (RU) is placed in between a group of fuel cells. The hydrocarbon fuel is first fed into the RU where it is reformed partially to hydrogen and carbon monoxide fuel using heat produced by the fuel cell electrochemical reactions. The reformed gases are then fed to the DIR chamber, where the residual fuel is reformed simultaneously with the electrochemical fuel cell reactions.

ERC plans to offer commercial DFC power plants in various sizes, initially focusing on the MW-scale units. The plan is to offer standardized, packaged MW-scale DFC power plants operating on natural gas or other hydrocarbon-containing fuels for commercial sale by the end of the decade. The power plant design will include a diesel fuel processing option to allow dual fuel fixed DOD base applications. These power plants, which can be shop-fabricated and sited near

the user, are ideally suited for distributed generation, industrial cogeneration, and uninterrupted power for military bases. After gaining experience from the early MW-scale power plants, and with maturing of the technology, ERC expects to introduce larger power plants operating on natural gas and/or coal gas or other fuels in the early part of the 21st century.

ERC operated a 1.8 MW plant in 1996-97, the largest fuel cell power plant that ever operated in North America, at a utility site. This first-of-a-kind power plant has demonstrated high efficiency, low emissions, reactive power, and unattended operation capabilities. These accomplishments are addressed in a separate paper at this conference. Built on the experience of this full-size power plant field test, ERC launched the Product Design Improvement (PDI) program sponsored by government and the private-sector cost-share. The PDI efforts are focused on technology and system optimization for cost reduction, commercial design development, and prototype system demonstration.

## **2.0 OBJECTIVES AND APPROACH**

This program is designed to advance the carbonate fuel cell technology from the current full-size field test to the commercial design by the turn of this century. The specific objectives selected to attain the overall program goal are:

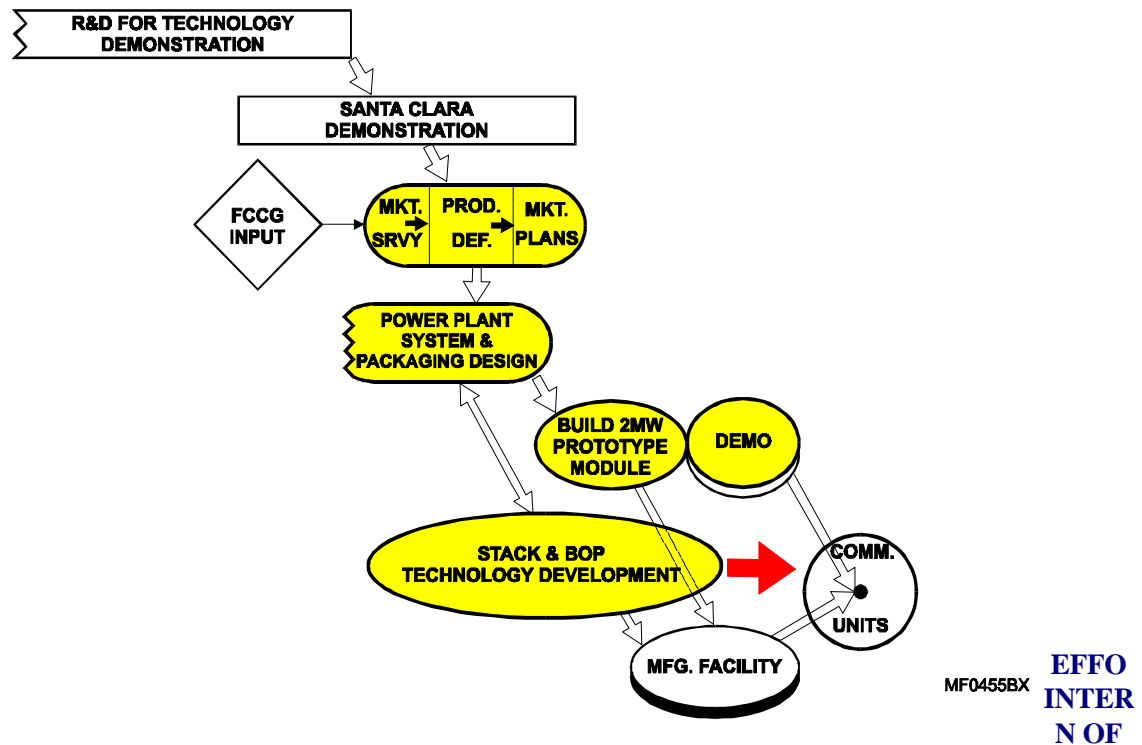
- Define power plant requirements and specifications,
- Establish the design for a multifuel, low-cost, modular, market-responsive power plant,
- Resolve power plant manufacturing issues and define the design for the commercial-scale manufacturing facility,
- Define the stack and balance-of-plant (BOP) equipment packaging arrangement and module designs,
- Acquire capability to support developmental testing of stacks and critical BOP equipment to prepare for commercial design, and
- Resolve stack and BOP equipment technology issues, and design, build, and field test a modular prototype power plant to demonstrate readiness for commercial entry.

A seven-task program, dedicated to attaining the objectives in the areas noted above, was initiated in December 1994. Program accomplishments of the past year is discussed in this paper. The previous year's progress was reported earlier[5-6].

## **3.0 PROJECT DESCRIPTION**

ERC is currently in the third year of the multiyear program for development and demonstration of a MW-class power plant supported by DOE/FETC with additional funding from DOD/DARPA and the ERC Team. Figure 1 shows key program elements (shaded area) and their interrelationships. The product definition and specification have been derived with input from potential users, including the Fuel Cell Commercialization Group (FCCG). The baseline power plant

final design has been completed. Detailed power plant system and packaging designs are being developed using stack and BOP development results. A MW-scale prototype modular power plant representative of the commercial design is planned to be constructed and tested. Based on the experience and data generated in the current program, ERC also plans to acquire manufacturing capability for market-entry products through expansion of the existing Torrington production facility.



**Figure 1.**  
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#### KEY PROJECT ELEMENTS:

The Program will Result in the Market Entry Commercial Product Design

A project team is in place to supplement all relevant expertise required for product design, improvement, verifications, and marketing.

## 4.0 RESULTS/ACCOMPLISHMENTS

In the past year, the ERC team has made steady progress in the areas of system design, enhancing manufacturing capabilities, resolving technology issues, and preparing for system verification. Major accomplishments in each of these areas are discussed below:

### Power Plant Design

The ERC team has completed the Final Design engineering effort of the baseline DFC power plant in collaboration with Fluor-Daniel, Inc. This design effort has already factored in the Santa Clara

Demonstration Project (SCDP) operating experience. The highlights of the SCDP operating experience input include improvements to the anode exhaust oxidizer, inverter electrical configuration, and plant layout for heat loss and maintenance considerations. The cost impact of the SCDP experience driven improvements/adjustments has also been evaluated and audited by an independent consultant and found to be within 1% of an earlier prediction[6]. The baseline plant is highly modularized featuring high efficiency, quiet operation, negligible emissions, and a small footprint that allows it to be sited in virtually any location. The plant has a rectangular footprint with a plot area of <420 square meter. The height of the plant will not exceed 7.6 meter. The DFC plant is designed for natural gas fuel, but modifications will allow use of other fuels such as landfill gas, and military logistic fuels. The plant will provide unattended operation with remote dispatching capability. The power plant specifications and engineering drawings available from the effort are sufficient to initiate the standard power plant procurement and construction activities.

The packaging approach for BOP and the stack module has been defined. The BOP equipment will be packaged into truck-transportable skids, complete with pre-installed piping, valves, insulation, instrumentation and electrical wiring. The truck-transportable fuel cell stack modules, each containing four fuel cell stacks and gas distribution to and from those stacks were, designed in conjunction with Jacobs Applied Technology, Inc. Progress in defining the stack module design is discussed later in this report.

## **Manufacturing Capabilities**

The stack manufacturing has been significantly enhanced by expanding the floor space, acquiring new tooling, and automating the quality check procedure for the cell packages. About 1300 meter square additional manufacturing floor space has been added to the existing manufacturing plant space of 5000 meter square. The components manufacturing processes have been streamlined to improve throughput, yield, and quality. FCMC has also prepared a semiautomatic full-height stack assembly facility. This facility will be used for assembly of the 300 plus cell stacks, the building block of ERC's DFC power plant. As the commercial components manufacture has been defined, the plant layout for the 24 MW/yr production capacity have been identified. Facilitization in accordance with this plan has been initiated. The present equipment capacity is approximately 17 MW/yr.

In parallel with manufacturing capacity enhancement, the components manufacture processes were improved and streamlined. The bipolar plate design has been refined to reduce thermomechanical stress and cost as well as improve mass manufacturability. Following successful qualification of the innovative design in the full area cell stack, the bipolar plate high rate manufacture tooling was designed, fabricated, and qualified in trial runs at the vendor's site. Next, the tooling will be commissioned at the Torrington, CT, manufacturing site. An automatic cathode manufacturing line has been commissioned to manufacture a fully quality-checked cathode every six minute starting with nickel powder. A photograph of the automatic cathode manufacturing line is shown in Figure 2. The matrix manufacturing rate and yield have also been increased using a lower cost casting substrate.

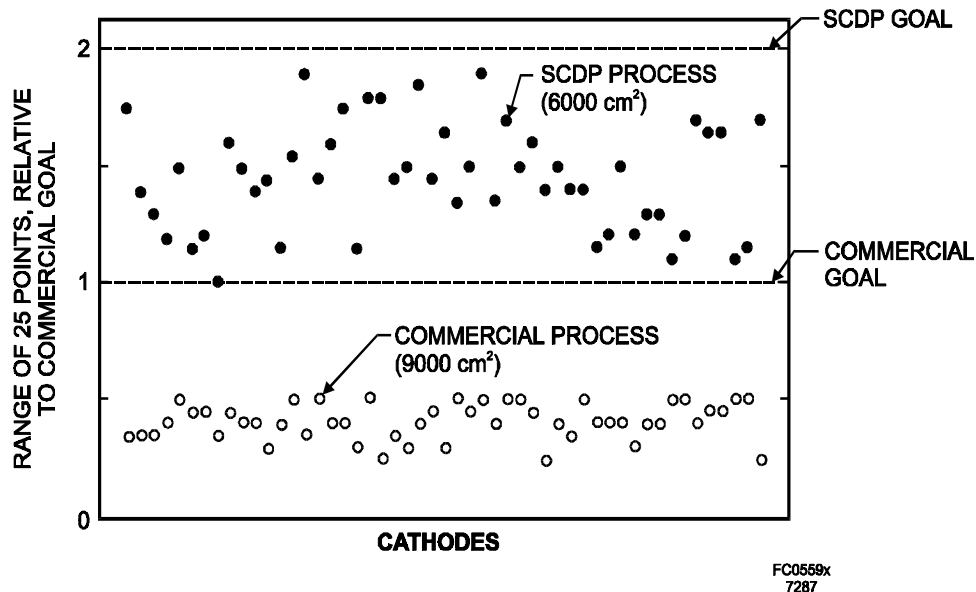


**Figure 2. AUTOMATIC CATHODE MANUFACTURING LINE:**  
Can Produce One Cathode Every Six Minutes

The cell components are quality checked by measuring thickness at twenty-five locations with a computer controlled thickness measuring machine. A photograph of the setup is shown in Figure 3. The range of the twenty-five measurements, i.e. the difference between the maximum and minimum values, is used as the individual components acceptance criteria.

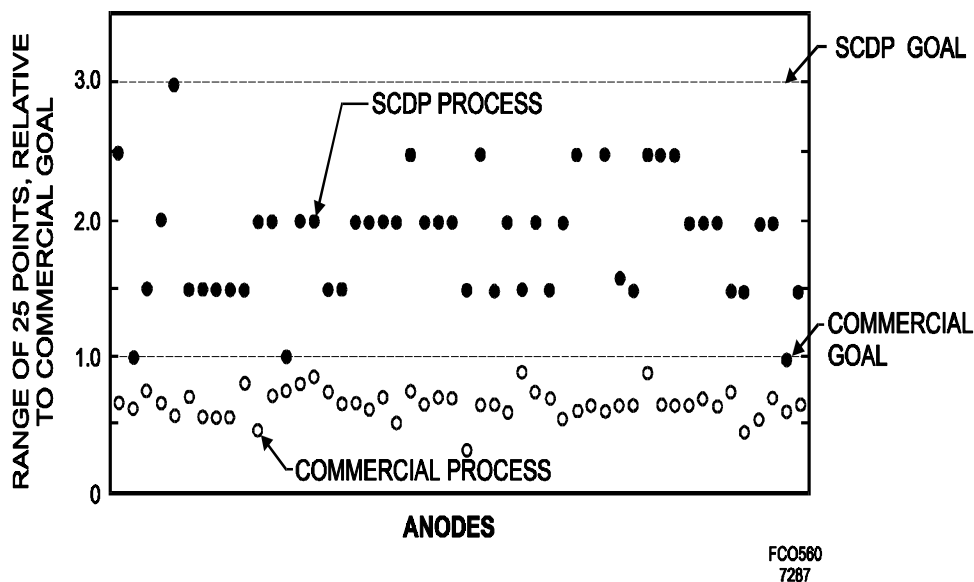


**Figure 3. COMPUTER CONTROLLED THICKNESS MEASUREMENT EQUIPMENT:**  
Thickness is Measured at Twenty-Five Points for Quality Check

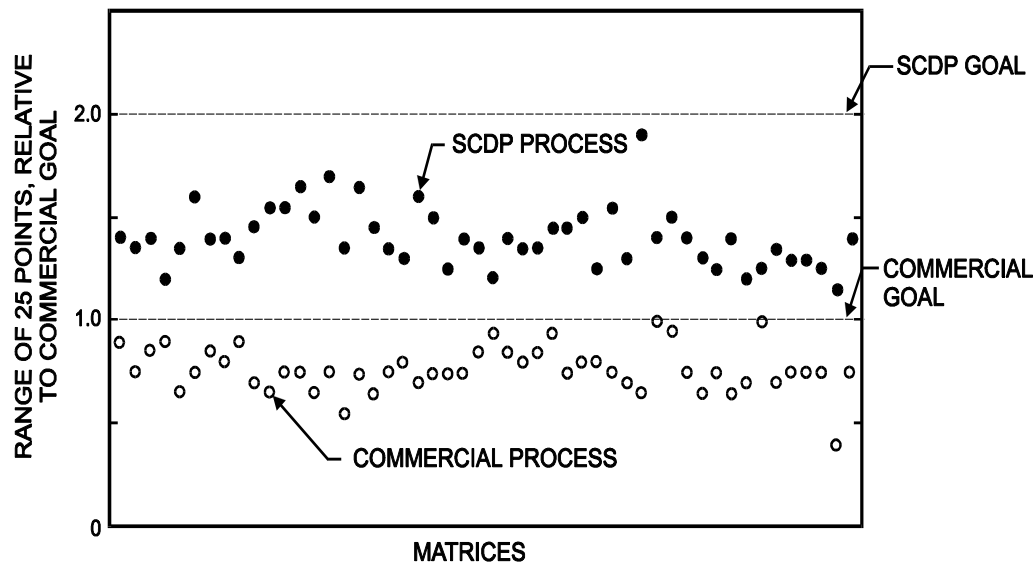


**Figure 4. COMPARISON OF THICKNESS RANGE OF COMMERCIAL PROCESS CATHODES WITH SCDP PROCESS CATHODES:**  
Thickness Variation Reduced by a Factor of Three

Together with the area scaleup, manufacturing rate, yield, and manufacturing tolerance of the cell components have been enhanced significantly. A comparison of the new generation 9000 cm<sup>2</sup> cathode quality measurement data (of fifty pieces of cathodes) with the previous generation 600 cm<sup>2</sup> cathodes is provided in Figures 4. The cathode thickness variation has been reduced by a factor of three and the piece-to-piece reproducibility, as shown by the scatter of the individual cathode measurements, has also been improved significantly. Similar quality improvements have been achieved for the anodes (Figure 5) and the matrices (Figure 6).



**Figure 5. COMPARISON OF THICKNESS RANGE OF FIFTY COMMERCIAL PROCESS ANODES WITH SCDP PROCESS ANODES:**



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**Figure 6. COMPARISON OF THICKNESS RANGE OF FIFTY COMMERCIAL**

**PROCESS MATRICES WITH SCDP PROCESS MATRICES:**

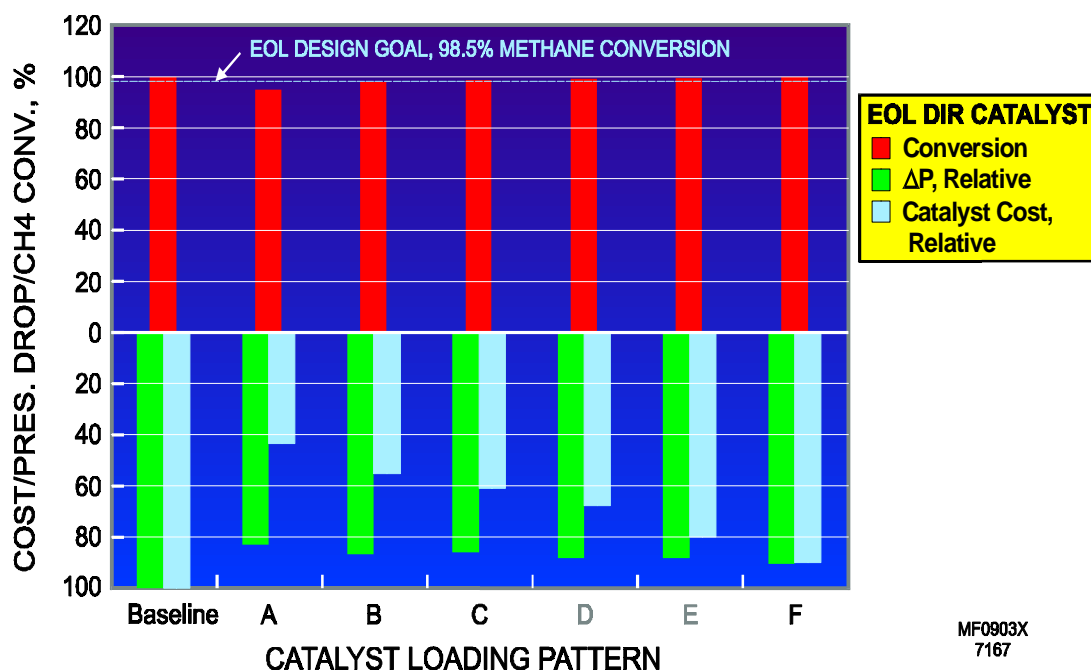
**Thickness Variation Reduced by a Factor of Two**

### Technology Improvement

A three-dimensional transient/steady-state computer model, describing fluid flow, heat and mass transfer, and chemical and electrochemical reaction processes has been developed based on the COMMIX computer code[8] for guiding the direct carbonate fuel cell stack design optimization. The computer model predicts three-dimensional distribution of gas flows, temperature and gas components as well as cell current density profile, cell potential, and pressure drops. The prediction is derived from numerical solutions of the conservation equations of mass, momentum and energy coupled with reaction kinetics and cell performance model. The models in the computer code have been validated by extensive laboratory data. Reasonable agreements between computed and fuel cell results, such as flow variations, temperature distributions, cell potentials, exhaust gas compositions, and methane conversions were obtained. Details of the model and modeling results with experimental DFC stack data were presented in a recent paper[9].

The model is being used at ERC as a cost effective tool for: 1) the DIR and reforming unit design optimizations, 2) evaluating stack performance (temperature profile, cell voltage, and pressure drops), and 3) investigating transient response to load changes. An example of the model utilization for optimization of the DIR design is discussed next. Six different catalyst loading designs were evaluated using the model. The model predicted end-of-life (EOL) methane conversion, anode chamber pressure drop, and the catalyst cost are compared in Figure 7. The Design E which promises 10% pressure drop reduction, 20% catalyst cost reduction over the baseline design and at the same time assures greater than 98.5% methane conversion at EOL (end-of-life) has been selected for stack testing.



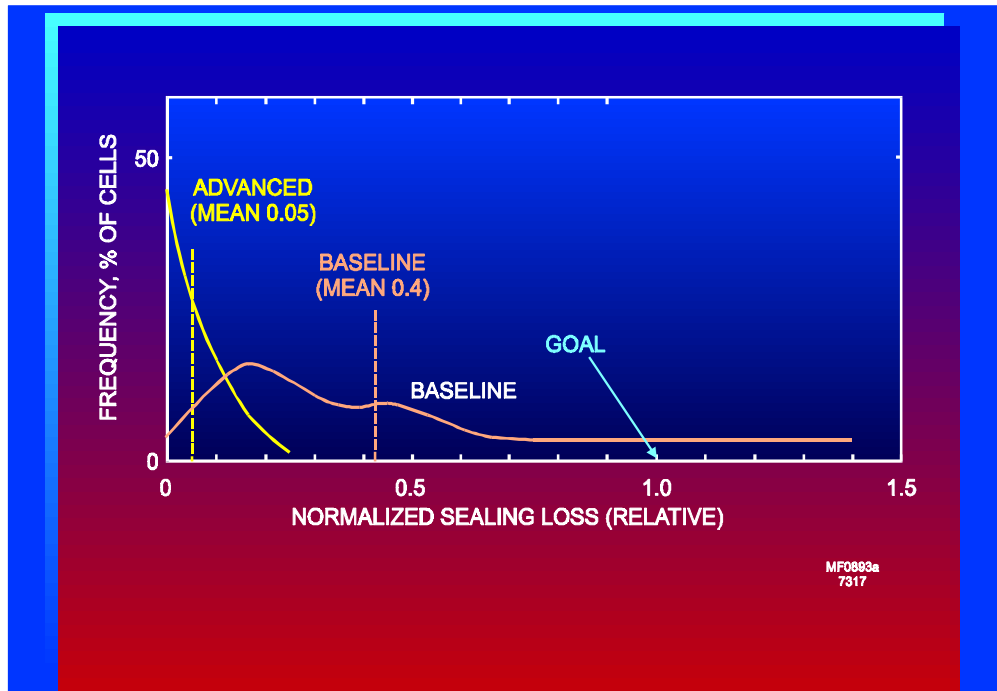


**Figure 7. DIR CATALYST LOADING PATTERN OPTIMIZED USING MODEL:**  
Design E Selected for Stack Evaluation

A high performance rugged matrix has been developed in a DOE/SBIR program and incorporated in the baseline DFC stack design. This matrix has resulted in excellent gas sealing capability and performance reproducibility in the DFC cells. A comparison of beginning-of-life gas sealing performance of laboratory cells (250 cm<sup>2</sup>) are compared in Figure 8 for two types of matrices, the advanced and the baseline designs. The frequency of cells, percent of the cells, is plotted against the gas sealing performance normalized with respect to the product goal. The laboratory cell data (built in 1996 to 1997 time period) show that for the cells built with the high performance matrix: 1) 100% of the cells met the design goal, 2) the mean gas sealing efficiency is approximately a factor of ten better than the design goal, and 3) cell-to-cell reproducibility is excellent. This improved design has also significantly enhanced thermo-mechanical ruggedness of the carbonate fuel cell.

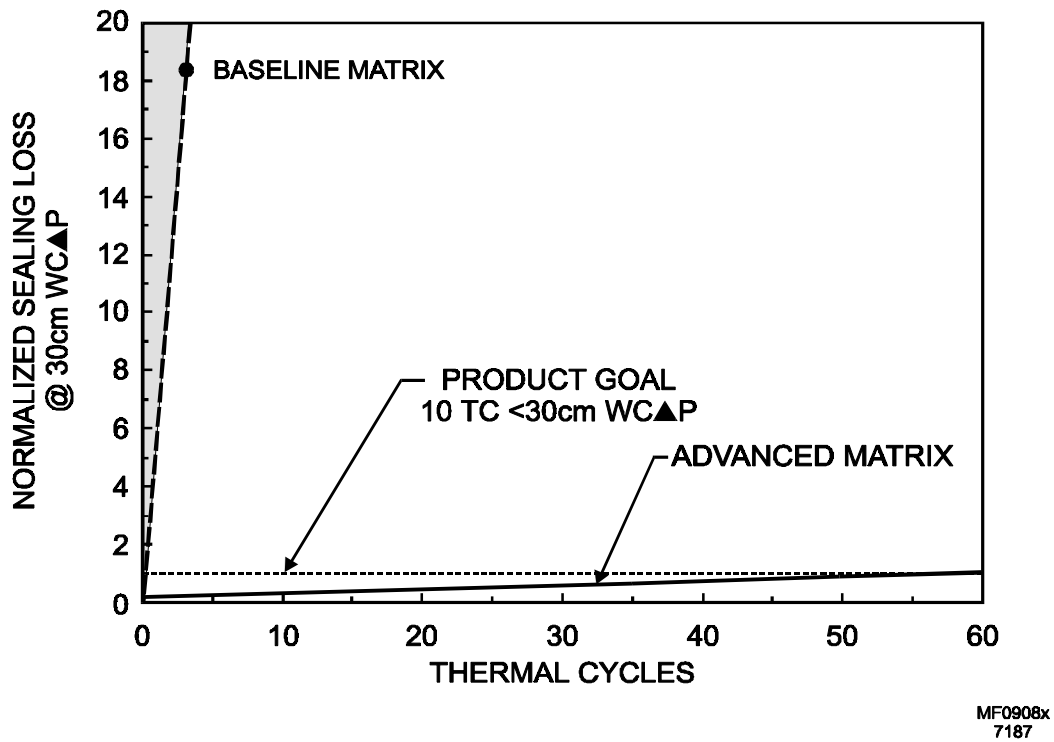
The DFC power plant targeted for the baseload power generation application is expected to undergo five to ten thermal cycles over its life for planned and unplanned maintenance operations. A laboratory cell built with the advanced design has already been thermal cycled sixty times (the test is continuing) using an accelerated scheme for gas sealing loss. The cell maintained the design goal for gas sealing (as shown in Figure 9). The gas sealing goal set here is very tight, <0.5% fuel loss at 30 cm of water column differential pressure which is equivalent to <0.2 % fuel cell performance loss. The cell electrochemical performance has also been unaffected by the repeated thermal cycles to room temperature (Figure 10).



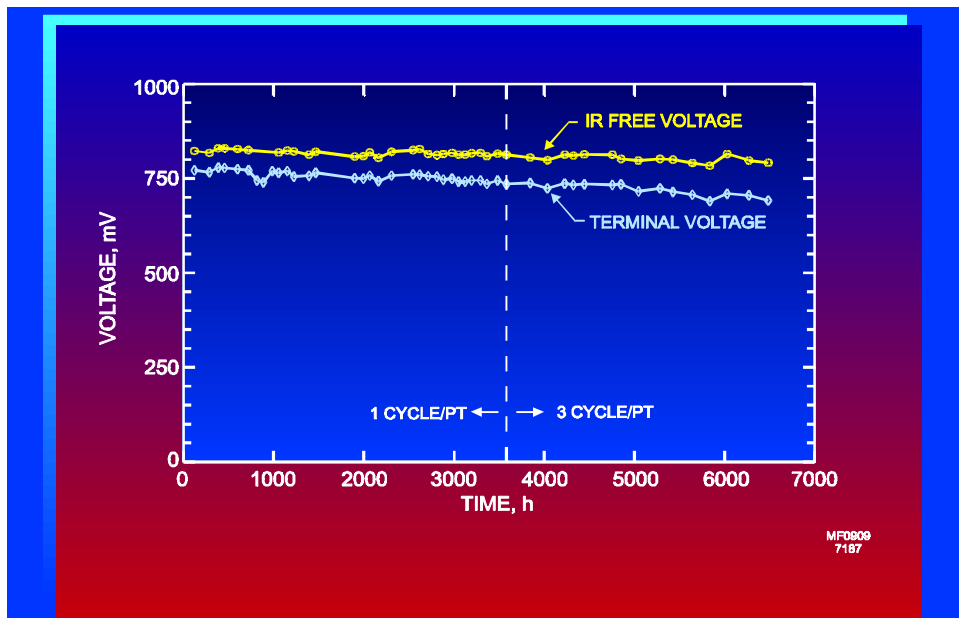


**Figure 8. COMPARISON OF GAS SEALING EFFECTIVENESS OF TWO TYPES OF MATRICES**

A Factor of Ten Improvement Achieved with the Advanced Matrices

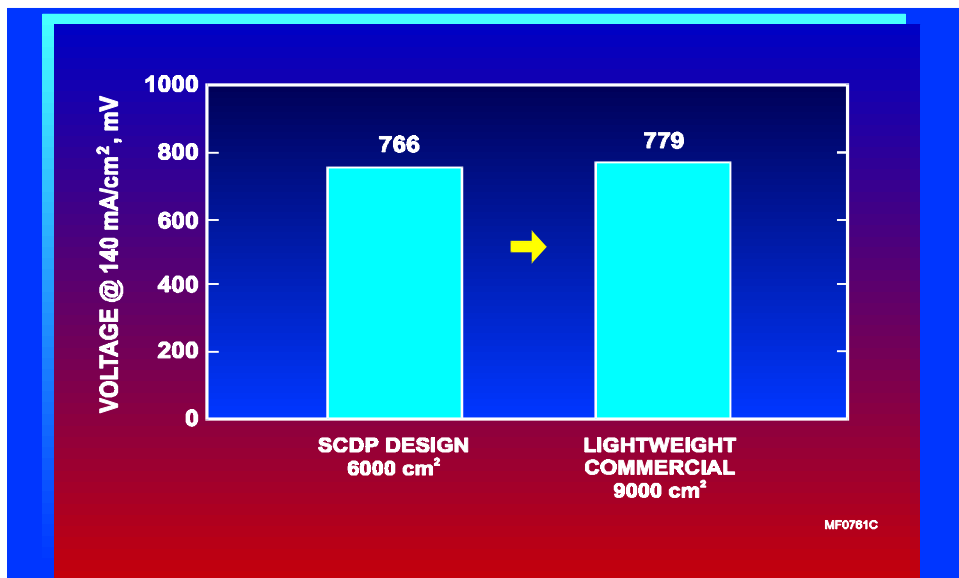


**Figure 9. EFFECT OF THERMAL CYCLING ON GAS SEALING:**  
Gas Sealing Goal Met Even with Sixty Thermal Cycles

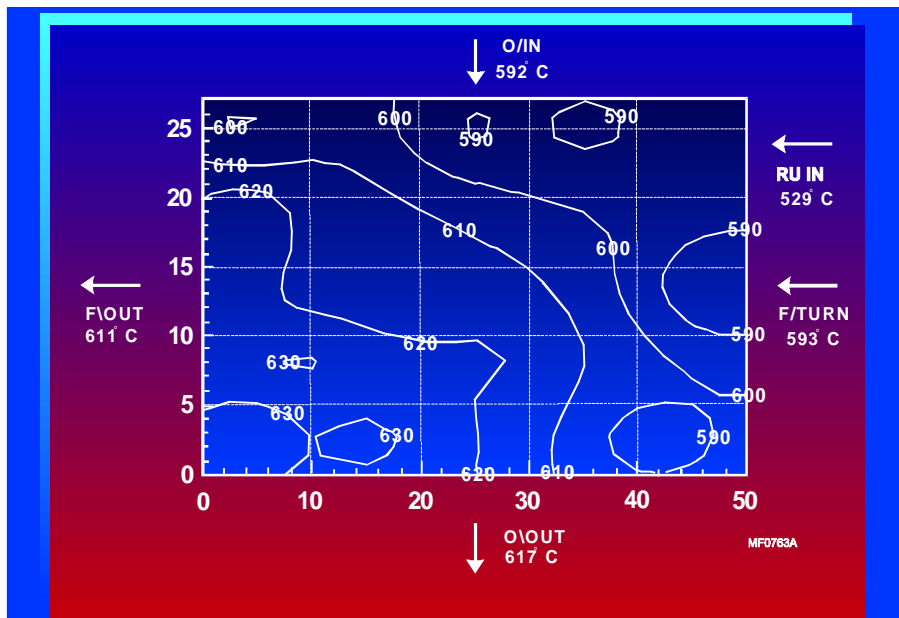


**Figure 10. EFFECT OF THERMAL CELL VOLTAGE:**  
Performance Unaffected by Thermal Cycles

The robustness of the commercial DFC design has been enhanced significantly by incorporating a thermo-mechanically compliant cell design and the advanced rugged matrix discussed earlier. The 10 kW-Class subscale stack (10-cell, 9000 cm<sup>2</sup>) test using this design has been initiated. The performance of this improved design stack is compared in Figure 11 with the Santa Clara generation 6000 cm<sup>2</sup> area stack. This lightweight, robust stack provided about 2% performance enhancement. The stack was operated at 160 mA/cm<sup>2</sup> producing ~1 kW per cell which is more than two times the cell power corresponding to the SCDP's maximum power operation point. The cell temperature distribution corresponding to the 160 mA/cm<sup>2</sup> operating case is shown in Figure 12. As the data show, the cell was operated with a temperature gradient of only 40°C even with a cold fuel inlet temperature of ~520°C. This improved thermal distribution has resulted from the optimization of the IIR as well as the DIR designs.

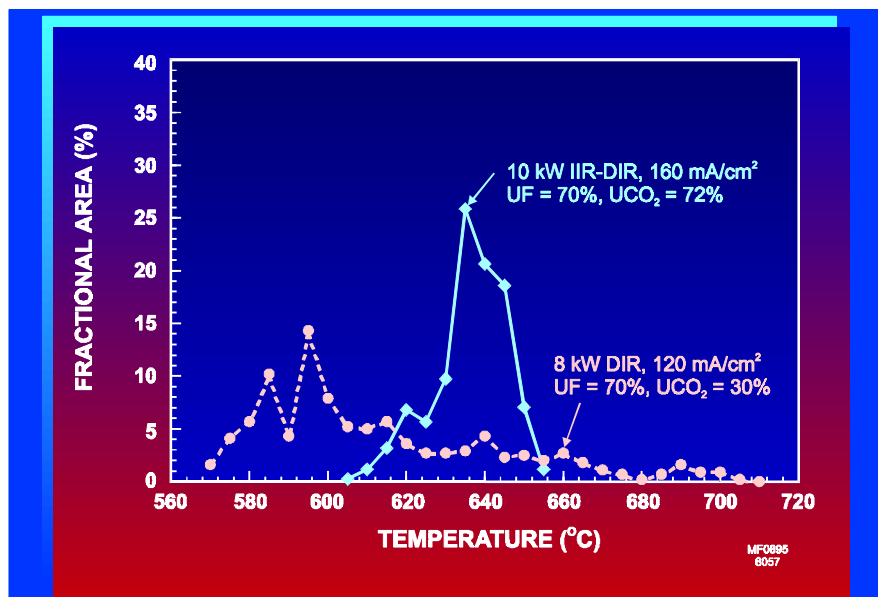


**Figure 11. PERFORMANCE STATUS:**  
~2% Performance Enhancement Achieved in Lightweight Full-Area Stacks



**Figure 12. TEMPERATURE PROFILE AT 160 mA/cm<sup>2</sup>  
(9000 cm<sup>2</sup>, 10-CELL DFC STACK):**  
Excellent Temperature Achieved at Rated Load

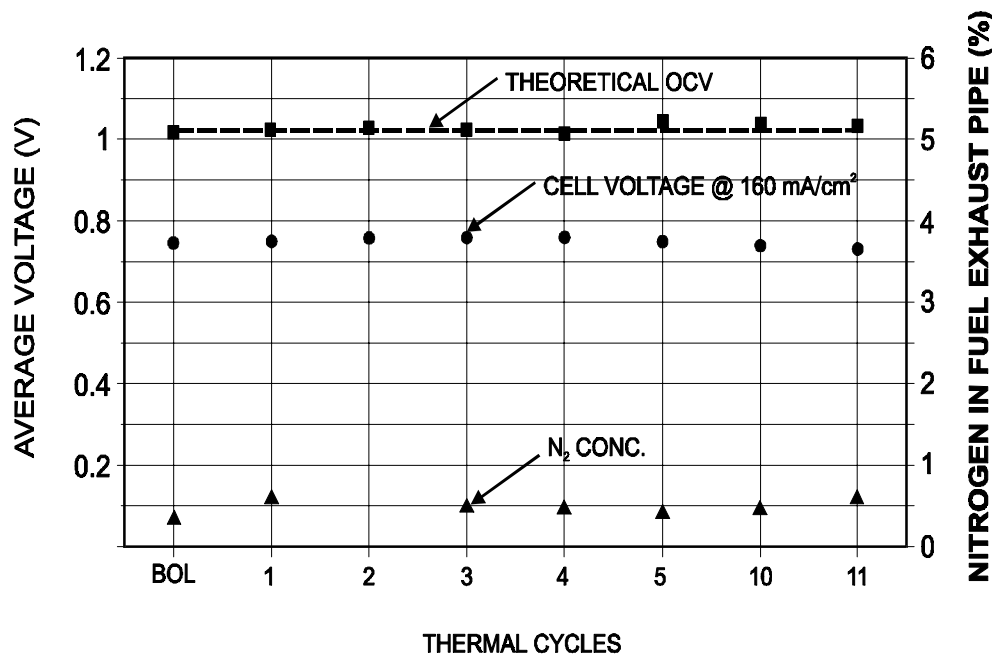
The IIR-DIR feature used in the ERC design lends to unique temperature control capabilities as compared to a DIR-only stack. This feature is illustrated in Figure 13, where the fraction of the cell area is plotted against the local temperature for two different internal reforming design types, the DIR and the IIR-DIR. These results point out that the IIR-DIR stack operates with a narrow temperature range. Therefore, for a given maximum cell temperature, the IIR-DIR design will provide the highest average cell temperature, hence, a better electrochemical performance. The baseline ERC IIR-DIR design can be optimized further by using the comprehensive DFC model discussed previously to fine tune the temperature profile.



**Figure 13. IIR-DIR AND DIR STACK TEMPERATURE DISTRIBUTIONS:**  
The IIR-DIR Provides Much Further Improved Thermal Uniformity

The 10 kW stack was thermally cycled eleven times without showing effects on gas sealing efficiency, electrochemical performance and cell internal resistance (Figure 14).

**Figure 14. EFFECT OF THERMAL CYCLING ON STACK**



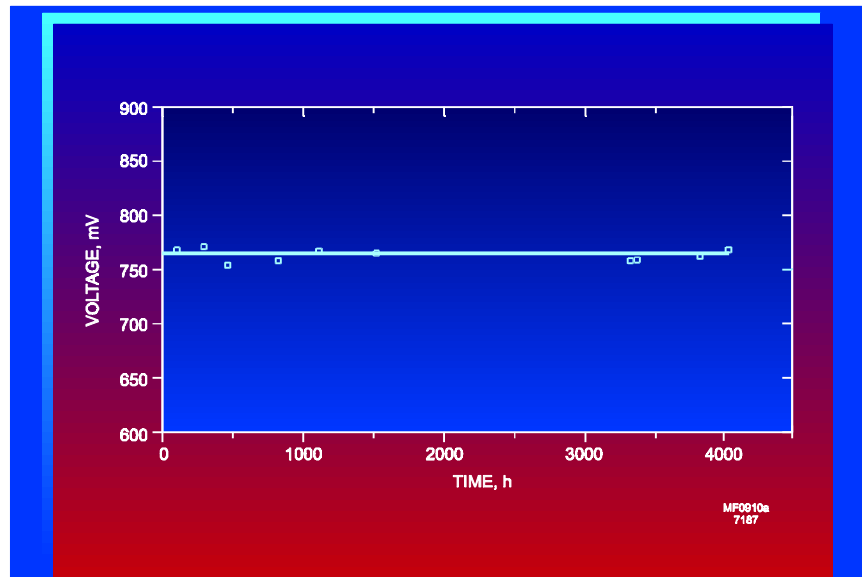
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#### **PERFORMANCE PARAMETERS:** Stack Robust to Thermal Cycling

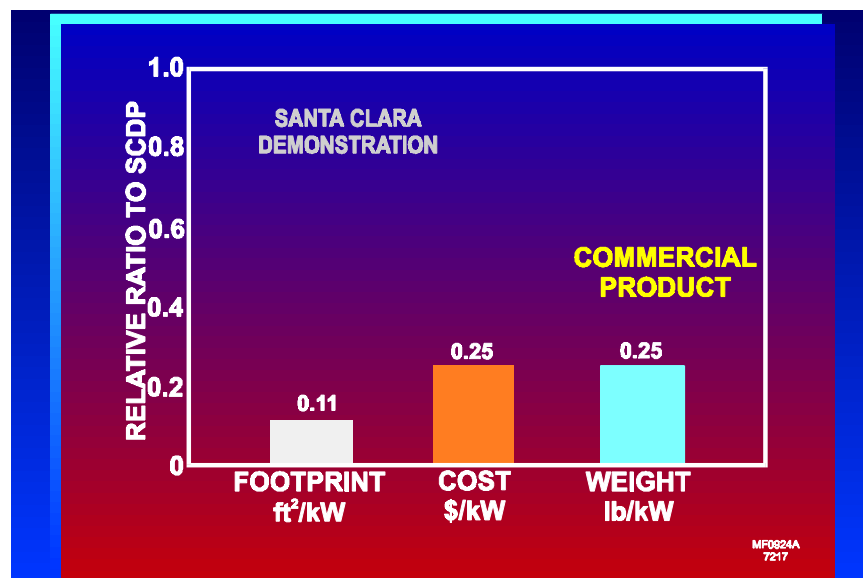
The baseline matrix uses a high surface area submicron gamma-LiAlO<sub>2</sub> powder as the matrix support material. Recently, the alpha-LiAlO<sub>2</sub> has been shown to be most stable in the carbonate environment. Use of this material is, therefore, expected to enhance matrix electrolyte retention in the carbonate fuel cell. The advanced matrix has been successfully fabricated using the alpha phase material. Two single-cell tests conducted with this material for greater than 4000 h each have demonstrated significant performance stability improvement. In fact, no decay in cell terminal voltage has been noticed in the initial data (Figure 15). The current focus is scale up of this design and implementation in full-area stacks.

Compared to the individually insulated stacks in a rectangular box used in the SCDP plant, the stack enclosure in the commercial product is an internally insulated circular box. The packaging, cost, and weight benefits of the new design are shown in Figure 16. On an equal output power basis, the stack enclosure footprint, weight, and cost have been reduced by factors nine, four, and four, respectively. The stack enclosure conceptual design was developed in 1994-95 time period. The important considerations for the design are: 1) high performance insulation, 2) electrical penetrations and conduction through hot environment, 3) internal gas distributors, 4) baseplate, and 5) packaging of four stacks and the gas distribution system within the truck transportable envelope. These designs have been evolved in 1996-97 time period through iterative stack tests. A multifunctional end plate which has integrated end plate and the stack compression plate functions has been made available (a

photograph of the plate is shown in Figure 17) from this effort. This design has resulted in elimination of end heaters, cathode side pipe dielectrics, and a 40% reduction of the expansion joints. To date six subscale tests of the stack module design have been completed. A full-height enclosure stack has also been fabricated for a test to be conducted towards the end of 1997. Based on the single stack enclosure experience, the four- stack enclosure design is being finalized. Once the design is finalized, a full-size simulator will be constructed for cold and hot verification tests. The four-stack module is truck-transportable. A “goose-neck” type transporter design is being finalized in collaboration with a transporter vendor.



**Figure 15. STABILITY OF ADVANCED CELL DESIGN:**  
No Decay Observed



**Figure 16. COMPACT STACK MODULE DESIGN:**  
Footprint Lowered by Factor of Nine



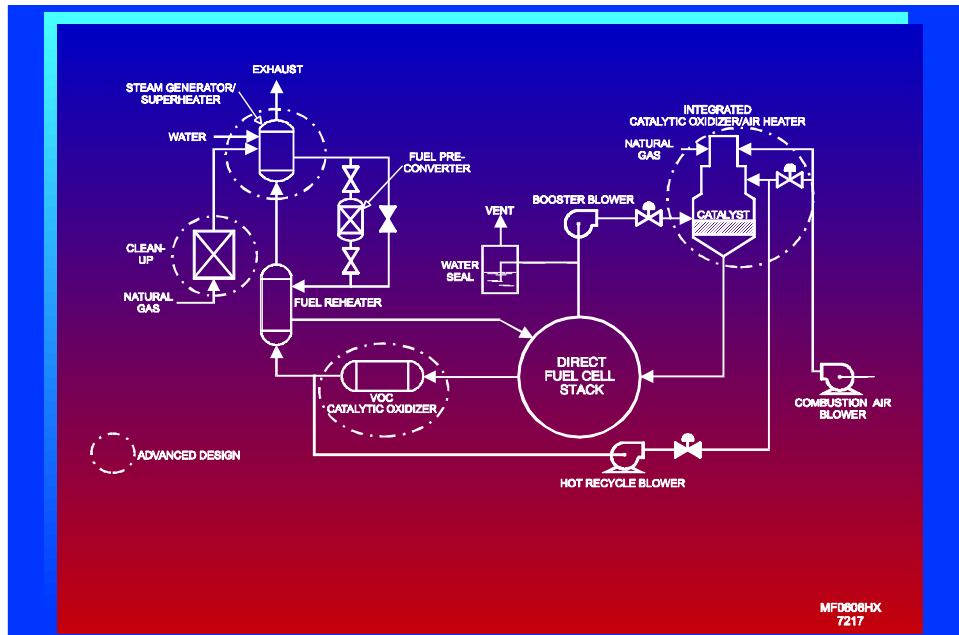
**Figure 17. MULTIFUNCTIONAL END PLATE DEVELOPED:**  
Eliminated Parts, Reduced Cost, and Allowed Compact Packaging

### System Design Verification

A 400 kW subscale power plant test facility has been constructed at ERC for evaluation of the major BOP equipment, full-size stack module, and power plant control and operational parameters. A process flow diagram of the power plant is shown in Figure 18. The power plant test facility includes a unique anode exhaust oxidizer design developed by ERC. The basic design has been validated by computer simulation in collaboration with the DOE/FETC in-house R&D engineers under a CRADA. This test facility simulates ERC's baseline power plant operations including automatic startup, shut-down, load change and steady state as well as provides conditioning of the full-size stack. The power plant construction and assembly have been completed (a photograph is shown in Figure 19). It is currently undergoing PAC (process and control test) and is expected to be ready for full operation by the fourth quarter of 1997.

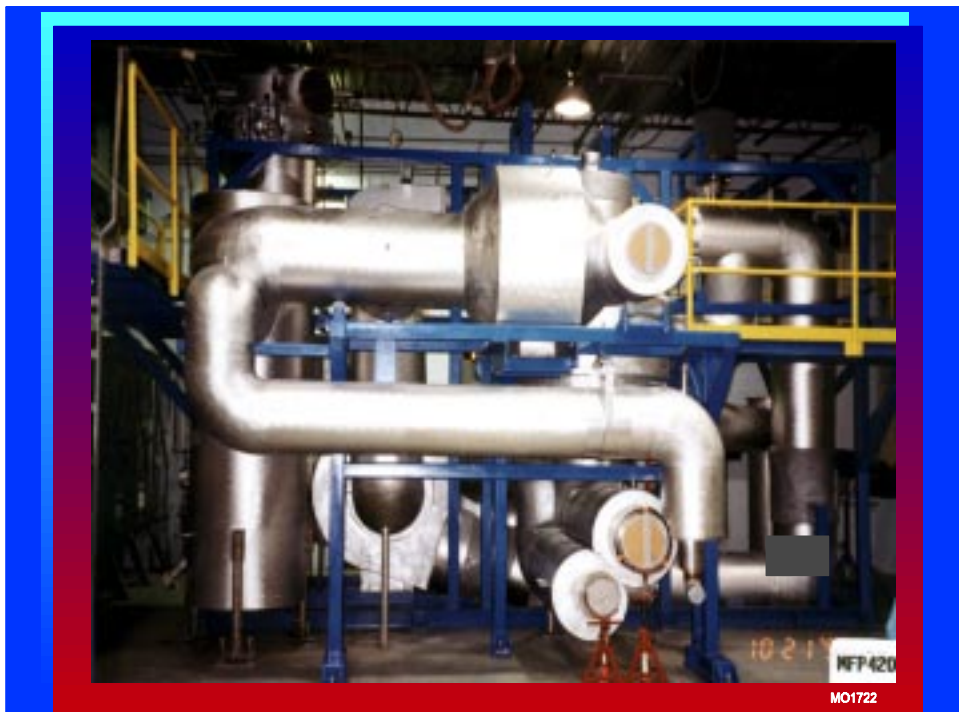
### Summary

The major accomplishments of the past year include the following: 1) completed baseline power plant final design and constructed 400 kW power plant test facility, 2) established commercial manufacturing processes for cell (repeat) components, 3) verified robustness of commercial cell design at subscale, and 4) verified stack module design in subscale stack tests; scaleup is in progress. The future activities will focus on testing full-size stacks and BOP equipment in the power plant test facility and construction of the stack conditioning facility.



**Figure 18. ERC 400 kW-CLASS POWER PLANT PROCESS FLOW DIAGRAM:**

Will be Used as Test Bed for Advanced Subsystems



**Figure 19. 400 kW POWER PLANT MECHANICAL CONSTRUCTION AND ASSEMBLY COMPLETED:**

This Power Plant test Facility will be Ready in the Latter Part of 1997



## ACKNOWLEDGMENT

The support of DOE and DARPA for the system and technology development and testing is gratefully acknowledged. The insight guidance and support of the FETC contracting officer's representative, Mr. Tom George, and DARPA representative Dr. Robert Rosenfeld are also appreciated.

## REFERENCES

1. *P. Patel, et al., "Internal Reforming for Natural Gas Fueled Molten Carbonate Fuel Cells", Final Report for the Period of May 1980 through June 1981 under GRI Contract No. 5080-344-0302.*
2. *P. Patel, "Internal Reforming Natural Gas Fueled Carbonate Fuel Cell Stack", Final Report for the Period of February 1982 through December 1983, under GRI Contract No. 5081-244-0545.*
3. *L. Paetsch, et al., "Molten Carbonate Fuel Cell Development", DOE Contract No. DE-AC03-76T11304, Final Report, April 1987.*
4. *M. Farooque, et al, "Development of Internal Reforming Carbonate Fuel Cell Stack Technology", Final Report for the period of February 1988 through September 1990, under DOE Contract No. DE-AC21-87MC23274, October 1990.*
5. *H. Maru, et al., "ERC Program Overview", proceedings of the Fuel Cell '95 Contractor's Review Meeting, DOE/METC, August 1995.*
6. *H. Maru, et al., "ERC Program Overview", proceedings of the Fuel Cell '96 Contractor's Review Meeting, DOE/METC, August 1996.*
7. *M. Farooque, et al., "Simulated Coal Gas Fueled Carbonate Fuel Cell Power Plant System Verification", Final Report under Contract No. DE-AC21-90MC27168, March 1995.*
8. *Argonne National Laboratory, COMMIX-1B: A Three Dimensional Transient Single-Phase Computer Program for Thermal Hydraulic Analysis and Multidimensional Systems, NUREG/CR-4348, ANL-85-42(1985).*
9. *Ding, J., et.al, " A Computer Model for Direct Carbonate Fuel Cells", Proceedings of the 4th International Symposium on Carbonate Fuel Cell, 191st Electrochemical Society Meeting, Montreal, May, 1997.*